Towards Nearly Zero-Energy Buildings through analyzing reasons for degradation of facades

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Abstract

Nearly Zero-Energy Buildings offer one way to reduce energy use in the built environment and thus contribute to mitigating global climate change. This paper is focused on analyzing the reasons for degradation of External Insulation Composite system facades in order to develop sustainable and cost-effective solutions for dwelling stock renovation. While several reasons for degradation of the facades have been studied in depth, the impact of building technology and site management have received undeservedly little attention. This paper systemizes the factors affecting facade quality and proposes a research plan for on-site surveillance in order to measure the weight of different degradation factors.

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Keywords: Nearly Zero-Energy Buildings, degradation of facades, thin-layer rendering systems, ETICS

1. Introduction

Thin-layer rendering on the exterior facade is one possibility to protect a wall against external effects. In European countries the External Thermal Insulation Composite System (ETICS) is widely used and the quality of its construction significantly affect the inner climate of the building. As the quality of renovated facades depends on a wide range of factors, it is essential to understand the importance of each factor influencing the performance of facades such as:

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• Holistic design and calculations (thermal insulation, moisture-diffusion, ventilation system, building services);
• External effects (weathering, pollution, direction of the facade, climate in general);
• Moisture and biologic growth (mortar composition, weather effects);
• Compatibility of used materials within the system;
• On-site construction technology (fixation, application of render).

These factors affect the degradation and further maintenance costs of the building. The research by Böhmer and Simon shows that 66% of buildings which do not meet the required energy efficiency level have shortcomings during the construction phase (Böhmer and Simon, 2011). This proportion highlights the significance of improving the construction process. By understanding and avoiding on-site deficiencies, it is expected that facade performance may be improved.

2. Problem recognition

The deterioration of the ETICS is influenced by numerous factors reducing facades’ lifetime. Many people have studied the reasons of degradation and made useful suggestions based on their research outcomes. However, there are still unsolved problems and there is a lot of space for improvement. The aim of this paper is to systemize these reasons for deterioration based on the literature and identify the knowledge gaps where further research input is needed. The degradation factors for ETICS are divided by degradation reasons into three main groups:

• Holistic design and defects caused by moisture;
• Composition of render mortars and use of substrates;
• On-site application of ETICS.

2.1 Holistic design and defects caused by moisture

The physics of the building, indoor climate and holistic design have to be integrated in the design stage to satisfy the goal of users and owners to reduce the maintenance and energy costs of the building during its operation (Mitterer et al., 2012). The research by H. Böhmer and J. Simon reveals the distribution of common design deficiencies as shown in Fig. 1 (Böhmer and Simon, 2011).

It is important to avoid thermal bridges as these lead to moisture and freezing defects (Böhmer and Simon, 2011). The moisture movement through the exterior wall should be minimized with an airtight interior layer to avoid moist convection damage (Künzel, 2010). The external rendering layer should control and manage rainwater to provide durability and prevent cracking of the exterior layer (Lstiburek, 2007).
During natural aging, most buildings get covered with natural biological growth and, compared to masonry walls, the thin-rendered walls have slightly higher probability for microbial growth due to rain and condensation (Künzel et al., 2006). Several papers analyze these reasons and the subsequent impact on the lifetime of ETICS (Künzel et al., 2006), (Silva and Falorca, 2009). Results of these studies show that the increased biological growth is caused by a combination of weather conditions, chemical composition of renders and moisture effects. As ETICS have high U-values, the temperature on the exterior wall reduces during night, which leads to the condensation of moisture and is the reason for biological growth (Sedlbauer et al., 2004). Thin rendering on thermal insulation is an acceptable ground for the growth of bacteria because of air pollution ingredients, which stratify with rain on top of exterior facades (Künzel et al., 2006). The condensation of moisture on exterior walls increases the biological growth mainly on the northern side of buildings (in the northern hemisphere), which in turn gives a good platform for the growth of algae. Increased growth of mould has been observed on cold colours mainly and on southern sides (Johansson et al., 2010, Johansson, 2011). In comparison to buildings with higher thermal inertia, thin-rendered facades show higher surface humidity and have more potential for biological growth (Johansson et al., 2010). The roughness and porosity should be also taken into account as parameters for the development of these degradation effects (Barberousse et al., 2007). The key literature and their findings are shown in Table 1.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>H. Künzel</td>
<td>2006</td>
<td>Surface condensation during night-time and stratification of air pollution increases microbial growth on facades</td>
</tr>
<tr>
<td>M. Silva; J. Falorca</td>
<td>2009</td>
<td>The growth of organisms is influenced by moisture, chemical composition, external weathering and environmental conditions</td>
</tr>
<tr>
<td>S. Johansson</td>
<td>2011</td>
<td>The direction of the facade has an impact on the growth level</td>
</tr>
</tbody>
</table>

2.2 Composition of render mortars and the use of substrates

There is a variety of different render mortar mixtures. The dissimilarity of plaster composition (ice formations, salt crystallization and water movement) should be tailored for particular conditions (Arizzi et al., 2012). Mortars containing binders with higher water uptake are more harmful and can cause internal cracks which lead to detachment of the render. The areas exposed to external conditions need to be adapted for rainwater and salt absorption by capillarity (Arizzi et al., 2012). The choice of water-retaining admixtures has an impact on the degradation of mortars (Paiva et al., 2006). On the other hand, the additional components affect the workability and application performance. The render system properties, mortar composition, external factors and substrate characteristics form a complex mechanism that should be taken into account when studying the degradation of renders.

During the aging of materials the changes in porosity and pore characteristics have been noted as open porosity of thin-layer plasters increases in time (Bochen, 2009, Bochen et al., 2005). The change in porosity has an effect on absorption through pores and capillaries and, during freezing cycles, the icing leads to cracking of the render. Finally, the thermal insulation layer is more exposed to external moisture (Šadauskienė et al., 2009). This phenomenon should be considered as one of the degradation factors for rendered facades.

High moisture loads in colder climates (temperatures below 0°C) may provoke frost damage. Water repellent plaster coatings are necessary components of ETICS to reduce external moisture and related damage to the system. Due to night-time sky radiation the condensation occurs on the exterior side of the coating and leads to growth of microorganisms (Künzel and Fitz, 2006). According to their study additional research should be made to increase heat capacity of the rendering to reduce the formation of condensate. The key literature for degradation factors regarding substrates and composition are shown in Table 2.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Arizzi; H. Viles</td>
<td>2012</td>
<td>Mortar composition has an effect on adhesion, ice formations and salt crystallization</td>
</tr>
<tr>
<td>H. Paiva; L. M. Silva</td>
<td>2006</td>
<td>Mortars containing binders with higher water uptake are more harmful and have increased rate of internal cracking</td>
</tr>
<tr>
<td>J. Bochen; S. Gil</td>
<td>2005</td>
<td>During successive weathering, the open porosity of thin-layer plasters increases in time</td>
</tr>
</tbody>
</table>
2.3 Field research and on-site application of ETICS

P. Gaspar and J. de Brito have published field research in which 150 facades of at least 30 year old buildings have been visually examined (Gaspar and Brito, 2005). It is important to keep in mind that their research reflects the situation where the layer of render is directly applied onto brick walls without external insulation. The outcomes of their research is summarised in Table 3.

<table>
<thead>
<tr>
<th>Degradation area</th>
<th>Share of degradation reason (%)</th>
<th>Differential cracking</th>
<th>Shrinkage cracking</th>
<th>Dampness</th>
<th>Staining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous wall</td>
<td>21,2</td>
<td>19,8</td>
<td>19,2</td>
<td>13,0</td>
<td></td>
</tr>
<tr>
<td>Around window openings</td>
<td>69,8</td>
<td>-</td>
<td>18,2</td>
<td></td>
<td>4,5</td>
</tr>
<tr>
<td>Bottom (floor level)</td>
<td>8,0</td>
<td>18,8</td>
<td>17,4</td>
<td>20,0</td>
<td></td>
</tr>
<tr>
<td>Corners and edges</td>
<td>56,0</td>
<td>6,0</td>
<td>15,2</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Top (parapets/eaves)</td>
<td>30,6</td>
<td>4,8</td>
<td>36,2</td>
<td>15,2</td>
<td></td>
</tr>
<tr>
<td>Below balconies and soffits</td>
<td>29,6</td>
<td>9,8</td>
<td>18,0</td>
<td>16,4</td>
<td></td>
</tr>
</tbody>
</table>

The outcome of this research shows that, in distinct areas, different causes of degradation dominate and it is useful to separate the probability factors. Different factors (wind, pollutants, sunlight, rain, biological growth) expose a combined threat to the lifetime of exterior layers (Gaspar and Brito, 2008). As the minor damages can expand to more harmful cracks, it is recommended to prevent cumulative damage by local cleaning and repairing (Flores-Colen et al., 2008).

2.3.1. Parameters to consider during on-site application of plasters

As thin-rendering facade is a composite system, every aspect of degradation should be differentiated by layers. It is essential to monitor the application of materials during the construction process and compare the building technology used with applicable requirements. By using one-coat rendering, the external layer has an aesthetic and functional purpose and, during kneading, on-site water is added to the mixture. The additional water is essential to approve the workability for application. According to research under laboratory conditions (Fernandes et al., 2005b), the following variables should be considered during the mixing and application process: nature and amount of kneading water, mixing time, setting conditions (temperature, moisture level, time) and external agents during use (e.g., CO₂, fungus). The final outcome of this study shows, that additional water has an essential impact on the curing, mechanical strength and porosity. It is recommended to use a w/c ratio between 21% and 23%. The curing process can cause surface cracking and micro cracking. During the first 5 or 6 hours after application of the plaster, the shrinkage rate is the highest (Hernández-Olivares and Mayor-Lobo, 2011). Therefore, the external weather conditions during the curing period must be observed. As an extended mixing time increases and a longer resting time decreases the amount of included air in the fresh mortar, they determine the properties of single-layer plasters (Fernandes et al., 2005a, Fernandes et al., 2005b). It is therefore necessary to supervise the on-site procedures to ensure the resistance of the external layer to degradation.

The weather conditions affecting the curing process can be very different during the application of the external layer. Manufacturers' manuals (Ceresit, 2013a, Ceresit, 2013b, MT_Grupp_OÜ, 2013) recommend the temperature range to be +5°C to 25°C and relative humidity 60%. It is proved in laboratory conditions that high temperatures increase the fracture energy and high humidity has the opposite effect (Nilica and Harmuth, 2005b). Thin-layer plasters applied under different conditions may lead to mechanical failure of the external shell.

In the process of on-site application, the thickness of the layer can also differ within a specific range. The guidelines given by manufactures are mainly prescriptive, while on-site it is difficult to apply an even layer and avoid joints. The increase of thickness of painted thin-layer render leads to higher vapour resistance which affects the wall’s moisture state (Šadauskiene et al., 2009). The emerging problem may be solved by increasing vapour resistance of the interior wall. The absence of air tightness in a building envelope may lead to degradation of the render.

The construction materials may have different moisture levels when installed. It generally depends on the storage and local weather conditions. After a water repellent exterior layer is applied, the drying of ETICS will finish after
some time. The high moisture level of construction elements leads to moisture-induced damage and a higher mould growth rate (Salonvaara and Karagiozis, 1999). Therefore the water content level of the construction materials should be considered when deciding the application time of layers with higher vapour resistance.

It happens quite often in the construction process that some elements of the system or materials are replaced by the contractor for various reasons (cost, lack, etc.). As a result, the initial system, which was recommended by the designer based on calculations to ensure the sustainability of the building, is altered. Renovated buildings do not achieve the intended energy consumption level caused within 34% by inadequacies or shortcomings in the design phase and 66% by improper execution during the construction phase (Böhmer and Simon, 2011). This means that the processes during the construction phase should not be underestimated. The same research reports the distribution of shortcomings during the construction process as shown in Figure 2.

To reduce or avoid the frequency of these shortcomings, it is recommended to use qualified craftsmen and increase quality controls. The designer, main contractor and owner should understand the correlation between different phases of the process (Böhmer and Simon, 2011). As the use and installation of insulation materials is one of the reasons for deterioration of ETICS, it is necessary to control the quality of insulation fixing. Thermal changes in material lead to shrinkage or expansion (Nilica and Harmuth, 2005a). Therefore, the areas which are fixed inadequately are liable to exhibit internal movement of materials and higher crack occurrence. The gaps between insulation panels lead to higher vapour transmission and these sectors on the exterior wall will have higher frost damage and mould growth risk (Sedlbauer and Krus, 2002). The key literature for degradation factors regarding on-site construction process are shown in Table 4.

![Fig. 2. Distribution of shortcomings during construction process](image)

Table 4. Key literature of degradation factors caused by on-site construction process.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>R. Nilica; H. Harmuth</td>
<td>2005</td>
<td>Thin-layer plasters applied under inappropriate conditions may lead to mechanical failure of the external shell</td>
</tr>
<tr>
<td>H. Böhmer; J. Simon</td>
<td>2011</td>
<td>Field study shows that 66% of buildings which don’t meet the required energy efficiency level have shortcomings during the construction phase.</td>
</tr>
<tr>
<td>K P. L. Gaspar; J. d. Brito</td>
<td>2008</td>
<td>Separation of degradation areas and factors on exterior facades</td>
</tr>
<tr>
<td>M.J.Silva; J. Falorca</td>
<td>2009</td>
<td>Surface defects (stains) lead to further cracking</td>
</tr>
<tr>
<td>O. Flores-Colen; J. de. Brito</td>
<td>2008</td>
<td>Wind, pollutants, sunlight, rain, biological growth - factors as combined threat to the lifetime of exterior layers</td>
</tr>
</tbody>
</table>
2.3.2 Overview of legislative materials, regulations and instructions on ETICS in Estonia

The main types of regulations which cover the area of construction works are: legal acts, national, EU and harmonized standards, commonly used descriptive instructions and Producer’s certificates and manuals. The overview of documents which regulate the ETICS application in Estonia are presented in table 5.

In a broad sense, we can say that legal acts and other compulsory documents (# 1 … 3) are too general for on-site management of the construction process. They do not contain specific technical regulations, descriptions of facade systems, nor technological instructions for on-site application. The same problem appears with different standards and technical specifications and ETICS certificates (# 4 … 8) – the technology instructions are missing or minimal. The only sources where the working process is explained are descriptive process guides and producer manuals. Regrettably available guides are compiled separately for insulation and rendering works but not for the ETICS as the system (#9), while producer installation manuals (#10) are strictly foreseen for specific products and do not contain general regulations and principles for facade systems nor freedom to replace some components of the system.

Table 5. Regulations and guidelines applicable for ETICS in Estonia.

<table>
<thead>
<tr>
<th>No</th>
<th>Type of the document</th>
<th>Short description of document content and its field of application</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Legal acts</td>
<td>General rules and frames for buildings, materials, procedures,</td>
<td>Compulsory</td>
</tr>
<tr>
<td></td>
<td></td>
<td>surveillance, etc. Most important legal acts in Estonia are: Estonian Building Act, Occupational Health and Safety Act and Fire Safety Act.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>EU standards – harmonized</td>
<td>Mostly general regulations but also some specific principles and guidelines for certain facade-related building materials (plasters, mixtures, grids, dowels etc.</td>
<td>Compulsory</td>
</tr>
<tr>
<td>4</td>
<td>EU and Estonian national standards</td>
<td>EVS and EVS-EN standards. These are mainly related to insulation materials, calculations of thermal resistance and moisture movement in external walls and design of inner-climate conditions in facilities, etc.</td>
<td>Optional, but strongly recommended</td>
</tr>
<tr>
<td>5</td>
<td>Most commonly used standards from different countries</td>
<td>Most commonly used national standards from different (Finnish - SFS, German - DIN, British - BS, Russian – GOST). These are mainly related to insulation materials, calculations of thermal resistance and moisture movement in external walls and design of inner-climate conditions in facilities, etc.</td>
<td>Optional, but recommended as subsidiary information</td>
</tr>
<tr>
<td>6</td>
<td>Technical specifications and reports (IEC, ISO, CEN, TS, TR)</td>
<td>Applicable for producers of construction materials and do not contain descriptions of facade systems.</td>
<td>Mandatory for producers</td>
</tr>
<tr>
<td>7</td>
<td>Descriptive guides and guides for facade systems, materials and quality-control</td>
<td>Descriptions and quality control requirements for different facade systems, and examples of typical solutions.</td>
<td>Optional, recommended as subsidiary information</td>
</tr>
<tr>
<td>8</td>
<td>ETICS certificates</td>
<td>Producers’ descriptions of ETICS components and their mutual compatibility. Helpful material for designers.</td>
<td>Optional, gives extra guarantee for owners and builders</td>
</tr>
<tr>
<td>9</td>
<td>Descriptive regulations for work processes managing</td>
<td>Finnish materials partly translated to Estonian. Contain work descriptions, guidelines for construction technology and the application process, qualifications requirements and output norms etc.</td>
<td>Optional, recommended as subsidiary information</td>
</tr>
<tr>
<td>10</td>
<td>ETICS installation manuals</td>
<td>Producer manuals. Contain specific and detailed description of product application, surface preparation, technology and sequence. Give guarantee if everything is done exactly according to manuals.</td>
<td>Optional, but strongly recommended</td>
</tr>
</tbody>
</table>

Of the above mentioned, only legal acts and harmonized standards are compulsory. Different instructive guides, producer manuals and technological regulations for the construction process are very helpful but could be used on a voluntary basis and these guarantee the quality only if all the procedures are followed exactly and no materials are replaced. However, the client can include into contracts the list of compulsory on-site technology requirements which could be a recommended way to gain control over quality de jure.
In conclusion we can say that there are too many requirements and guidelines in different documents which are difficult to follow and it is up to the project manager to decide if and how to follow them if there is nothing mentioned in the contract. The first outcomes of on-site monitoring which we are working on let us conclude that the abovementioned recommended guidelines are not really followed in the working process.

3. Further research framework

Further research is directed to evaluate the relative importance of construction technology shortcomings during the construction process of ETICS facades. It is unclear which factors have a higher impact on the lifetime of the facade and need to be studied more precisely. During the period from 1960 until 1990, 367,000 residential rooms in apartment buildings were built in Estonia (Smirnova and Sinisaar, 2009). These buildings have high energy consumption rates for heating (between 95 – 183 kWh/m²·m per year) and need renovation (Kalamees et al., 2009). As the reconstruction rate for these buildings is increasing, it is essential to evaluate the quality of the renovation previously carried out to avoid the most common defects in the future. To understand the scope of degradation of thin-rendered facades, 55 apartment buildings in Tallinn were selected. These are 4-storeyed buildings with flat roofs and walls from concrete panels or small blocks. The sample buildings were built from 1960 to 1990 and renovated from 2010 to 2012 and their minimum renovation scope was exterior facade.

Although the renovation works have been executed not more than 5 years ago, the visual observation made clear that there are significant deficiencies regarding the construction quality. The most common defects are cracks in specific nodes and insulation installation failures, which are the result of poor design and/or construction work as shown in Figure 3. These defects can be classified as defects caused by moisture, wrong design, wrong fixing and application faults.

![Fig. 3. Defects: a) moisture; b) wrong design; c) wrong fixing; d) wrong application](image-url)
The following framework for further research is proposed:

- Comparison of design documentation with regulations. This will reveal deficiencies in the design process.
- Comparison of design documentation with on-site documentation. This will show if the design documentation is in place and if it is followed, but also which designs are used as the basis for application, if any.
- On-site monitoring of the construction process. Numerous factors affecting the quality of facades will be monitored during on-site construction processes: conformity of used materials, weather conditions during application, application technology in compliance with the requirements, craftsmen skills and their impact on quality, etc. The monitoring scheme has to be compiled.
- Based on the analysis of the gathered materials it will be possible to systemize the degradation factors. The next phase of research will be devoted to evaluation of these degradation factors by their impacts on the degradation process. This will include on-site monitoring as well as simulation of degradation in the lab.

4. Conclusions

The final outcome in the quality of the building involves different aspects of the design and construction process. During the design phase the complex structure through correct calculations of thermal insulation, building services and ventilation must be resolved. As biological growth is a threat to the lifetime of the facade, suitable materials should be used, while the external factors (facade direction, local climate, air pollution, etc.) are taken into account. Unsolved rainwater drainage causes stratification of chemical composites on the external layer and eventually initiates biological growth and further degradation. The composition of render mixes leads to different ice formations, water movements and recommended application conditions, which all have an impact on resistance to cracking. Water repellent and other substrates have an effect on the durability and lifetime of the facade.

On-site construction technology is our focus of further research. The designers' and material manufacturers' recommendations should be implemented during the on-site application process. Even the details of the execution (amount of kneading water, mixing time, weather conditions, external agents, insulation fixation, etc.) may cause cracking of exterior layers. As most of the mistakes leading to low energy efficiency occur during the on-site construction process, the use of skilled craftsmen cannot be underestimated. The framework of research, introduced in this paper, will evaluate the weight of the on-site factors of degradation.

Acknowledgements

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References


Ceresit 2013a. CT 35 Mineraalkrohv.

Ceresit 2013b. CT 137 Mineraalkrohv.


